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DESIGN, TESTING AND CONSTRUCTION OF AIR AND LIQUID SOLAR HEATING SYSTEMS

Prepared for

MONTANA DEPARTMENT of NATURAL RESOURCES and CONSERVATION

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DESIGN, TESTING AND CONSTRUCTION OF AIR AND LIQUID SOLAR HEATING SYSTEMS

Prepared by

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May, 1978

Prepared for

Montana Department of Natural Resources and Conservation
32 South Ewing, Helena, Montana 59620
Renewable Energy and Conservation Program
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FINAL REPORT

I. Objectives of Project

The general objective of the project was to finish our alternative energy home started in 1975. Specific new objectives sought were to:

1. Develop a standard size fiberglass box for use in solar collector construction.
2. Install and evaluate radiant slab heat as a means of utilizing solar heated water.
3. Evaluate different air collector designs and compare to water systems.
4. Develop a wood backup stove specifically for solar energy.
5. Construct a cheap, reliable, electric backup unit.

With the completion of these objectives we now have functioning in our one location both air and water solar systems, several different utilization methods, and several different backup systems.

II. Project Implementation

As with most research projects, the scope of this project increased greatly once actual work was begun. For example, what started as a search for a method of developing a standard fiberglass box ended up comparing boxes of several designs. The original comparison of two types of air collectors ended with tests of six designs. Some questions not even remotely considered in the original grant application had to be answered before certain phases of the project could be completed. Hence a fairly in depth analysis and testing of insulation materials and paints evolved.

It is interesting that some of these "spin off" experiments yielded some of the more significant findings. Some of these "spin off" experiments were done as independent research projects for the University of Montana. I am including final reports of two such projects in this report because they may be of interest and prove helpful to others.

The five basic areas of my DNRC grant project are:

1. Water collectors
2. Air collectors (and shop remodeling)
3. Greenhouse radiant heat
4. Stove research
5. Backup heater

I will cover each separately and then make general recommendations and conclusions.

Water Collectors

CONTENT: Contains description of evolution of collector box and collector plate design.

1. Project Planning and Equipment Acquisition

The planning of this phase of the project was based around experience with previous collectors I had constructed. Among the problems being addressed was the weight and durability of the collector box as well as some moisture and condensation problems. Materials to test different box designs were hard to come by locally and out of state suppliers were chosen by necessity. The project called for construction of 200 $ft.^2$ of copper water collectors. Initial testing was accomplished before these were finally built.

2. System testing and Modification

My general method of operation is to test components and ideas in scale model before large scale building begins incorporating the best method or design. These experiments really represent the heart of this project and produced some of the most important findings.

A major question concerning flat plate collector design is the cost, weight, and durability of the box itself. I looked into this question in some detail. (See Solar Box Construction Report--pages 1 thru 6, attached).

An attempt was also made to remove all excess materials from the expensive collector face. Perhaps one of the most significant findings of the entire project was that most commercial and homebuilt collectors of copper are grossly over-designed and can be reduced by as much as 75% without sacrificing collector quality or efficiency. (See "Reduction of Collector Plate Material", pages 7 thru 12, attached.)

Reports in the literature indicated a green color may be superior to black for painting absorber plates. After several attempts to get information about this failed, I decided to test it myself. (See, "Plate Coating", pages 13 thru 18, attached.) Black came out the best, but not by much.

3. System Installation

System installation was relatively simple as all plumbing as well as pumps and storage tank were already in place. Installation took about two full days, using four people. Individual collector sections were lifted to the roof, connected together by clamps and heater hose, and slanted slightly so they could drain completely. A draindown valve was located at the highest point.

4. System Performance

The water collector system performs beautifully. Due to the fiberglass and foam box construction, excessive weight and moisture problems are absent. The system drains back into its heated storage tank every time the pump shuts off thereby eliminating freezing problems and expensive antifreeze and heat exchange problems. See "Reduction of Plate Material", pages 11, 12 and attached graphs for performance data on collector faces.

5. System Cost

Collector box, per square foot. (See "Solar Collector Box Construction", page 6)	.49
Collector face, per square foot	1.70
Foam insulation, per square foot	.65
Tempered glass glazing; includes silicone sealants & aluminum flashing	2.36
Misc.	.30
TOTAL sq. ft. cost of collector materials	$5.50

Air Collectors

CONTENT: Contains a description of the solar air system used to heat the shop.

1. Project Planning and Equipment Acquisition

The planning phase of this portion was difficult since I had no personal experience with air systems. I originally intended to build and compare two types of air collectors. Further investigation led to other types which deserved consideration, so I included these in a scale model testing program before deciding upon a style to build for my permanent installation.

2. System Testing and Modification

See attached research paper entitled "A Comparison of Air Collector Designs."

3. System Installation

The chosen design of the fiberglass wave type was installed on the south vertical wall of my shop. Considerable modification of the wall itself and insulating of the shop building were required. A concrete shelf was poured to support the collectors. Considerable custom ductwork was required. This portion of the project was completed approximately April 15th, 1978.

4. System Performance

There have been problems with the performance of this system. Excessive static pressure was encountered which required essentially redoing the entire setup. Most of the fiberglass "waves" had to be removed to get much air to flow at all. This helped the problem but it still takes a 1/3 Hp. motor and large fan of 1600 cfm capacity to push air through 216 square feet of collector. Compared to water systems this is very energy inefficient as the same job in water would require only 1/35 Hp. There is also no rock storage involved which would increase friction even more.

The problems are mechanical. As to the solar efficiency; that evaluation must wait. The sun is now striking the collectors at such an extreme angle and the overhang is shading the area to the degree that meaningful performance must wait for lower sun angles of winter. The actual vertical mounting of collectors I am pleased with, there appears to be little problem with high stagnation temperatures in the summer time due to the extreme sun angle of incidence.

All in all I am displeased with air systems compared to water systems.

5. System Cost

The box used is identical to the previously described one.

Collector box, per sq. ft.	$ .49
Foam insulation, per sq. ft.	.65
Glazing, sealant, flashing, per sq. ft.	2.36
Misc.	.30
TOTAL sq. ft. cost of collector materials	$3.80

Greenhouse Heat

CONTENT: Describes one method of using solar heated water for space heating, i.e. radiant slab heat.

1. Project Planning and Equipment Acquisition

A reprint taken from an older Architecture Handbook entitled "Heating Systems For Houses--Hot Water Radiant Systems", by William J. McGuinness, M.E., Professor of architecture, Pratt Institute, was particularly useful in planning the greenhouse heat. The system consists of copper pipe in an insulated concrete slab.

2. System Testing & Modification

This heating system is a tried andproven one with engineering data readily available. No testing was necessary.

3. System Installation

A normal system of this type is piping in a 4" insulated concrete slab. This type of installation was impossible in my greenhouse due to existing concrete and doorways. I had to, instead, install a slab of only 2½" thickness. A small pump controlled by a thermostat completes the installation.

4. System Performance

The system has performed very well. Because of the thinness of my slab, I was forced to use ½" copper pipe instead of a larger size more commonly used. I was therefore unable to get quite enough BTU's into it at lower water temperatures to carry the entire load. Hence on extremely cold nights a few times a year I must supplement it somewhat. However, 90% of the time it functions beautifully and I have no doubts this one drawback is the result of my particular situation. I consider this type of heating system to be the best one for use with a solar water system since it can use water clear down to temperatures of 100° F.

5. System Costs

Architectural handbooks list the cost of this type of heating system as about the same as forced air or hot water baseboard.

Stove Research

CONTENT: Describes the design and construction of alternative energy backup stove.

1. Project Planning and Equipment Acquisition

This stove was designed because many desirable features for a solar backup stove cannot be found in commercial units. Among the design criteria were:

a. Standard fitting for outside combustion air.

b. Preheated combustion air distributed both under and over the fire for primary and secondary combustion.

c. Damper control

d. The ability to recharge a rock storage for air systems and liquid storage tanks simultaneously.

e. Eliminate creasote problems.

Construction was of 3/16" plate steel welded together. The door was ½" steel decking with soft asbestos for sealing.

2. System Testing and Modification

The original combustion air inlet was 1¼" pipe fitting. This proved completely inadequate and was eventually enlarged all the way up to a 4" fitting. Likewise the original 6" stovepipe was replaced by 8" before the stove functioned properly. Considerable modification of the primary and secondary combustion air was also required.

3. System Installation

The stove is now installed in my shop. Outside combustion air is brought in through the roof using 4" sewer pipe, eliminating any draft infiltration caused by the combustion.

4. System Performance

The stove now burns beautifully. By carefully adjusting the controls after lighting a fire, one can hear the roar of secondary combustion starting. Left burning in this mode the stove puts out tremendous heat in what I think is nearly complete combustion. The smokestack shows nothing but heat waves coming out, not even white smoke. Throttled down with the damper for a slow burn, the smoke is a nice white color. The stovepipe remains nearly as clean inside as outside. No creasote problems have occurred and chimney cleaning should be rarely needed, if at all, when burned in this manner. The stove heats large amounts of water for storage as well as considerable hot air which can be ducted to any needed place. All in all I am extremely pleased with its performance.

5. System Cost

4' X 10' sheet of 3/16" steel	$104.19
½" decking for door	52.97
Pipe fittings and stovepipe	59.06
Firebrick	12.32
Misc.	10.00
Welding rod	10.00
High temperature paint	13.00
Subtotal	$261.54

Counting materials used which I had on hand, the total cost for materials in the stove is approximately $300.00.

Backup Heater

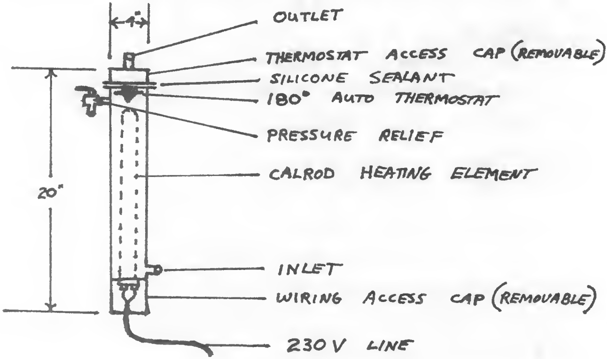
CONTENT: Describes the design and construction of an electric backup heater for use with a solar heated storage tank.

1. Project Planning & Equipment Acquisition

There is a need in some solar installations for a reasonably priced backup heater to boost water temperatures. At first it appeared there was a commercial unit which would do the job. Upon further examination, however, certain safety problems appeared. I then decided to build my own unit as originally proposed. This unit should be capable of raising the temperature of solar heated water for use in hot water baseboard systems as well as being used to heat water from a wind turbine source.

2. System Testing and Modification

The backup heater was built using 3" ABS or PVC plastic pipe, a 180° auto thermostat, a 5000 watt calrod heating element, and several fittings. Fiberglass was used to seal and mold the elements together. The following drawing illustrates the design.



The unit was tested using convection flow only, although a small pump could be employed. (See photo.) The heater performed quite well. Convection flow was adequate and the closing auto thermostat prevented backflow. The only modification I would make is to lower the heating element output to 3000 watts or so, or increase the outlet fitting from 3/4" to 1". The reason is that when the water is hot the 3/4" outlet pipe cannot quite carry the heat away fast enough and some boiling of the water occurs.

3. System Installation

Since I am still evaluating the feasability of a wind turbine at my site, the backup heater will not be installed at this time. If wind generation proves feasable at my site I wish to use this unit or one similar to provide heated water.

4. System Cost

4' of 3" PVC DWV pipe	$ 2.00
5000 watt $\overset{230}{320}$ volt calrod unit	10.00
180° automobile thermostat	5.00
Pressure relief valve	5.00
Four fittings	1.00
Fiberglass	10.00
Cost figures are for heater only	$33.00

Information Booklet

As per a request from Mr. Jan Koningsberg of the Montana Department of Energy, the information booklet I was originally to write was integrated into a Department of Energy publication. It was the feeling of all concerned that this publication would receive wider distribution and that my collaboration in it would prevent duplication of effort. I was very well satisfied with my contacts with Jan, and hope my inputs in this area have been beneficial and helpful.

III. Conclusions and Recommendations

This grant project, in general, has been quite successful. Most of the goals have been met or exceeded. Most equipment has perfomed at or above expectations. Perhaps the single most significant finding was the fact that copper plate thickness could be reduced by 75% without affecting performance. Further work needs to be done in this area, since theoretical calculations show that an even further reduction should be possible. When one considers the millions of square feet of copper flat plates to be constructed in the next few years, such a finding could be significant indeed!

The most important general findings of my grant project are:

1. Very thin copper can and should be used in flat plate construction. When this is done copper becomes cost competitive with other materials and far surpasses them in performance.
2. It is my opinion that radiant slab heat is the best utilization of solar heated water for space heating.
3. The fiberglass box on urethane foam eliminates the problems found in other box materials. Costs are comparable. Durability is greatly improved.
4. The solar backup stove performs beautifully and has features well worth incorporating.
5. Air systems do not compare favorably with liquid systems in efficiency.

IV. Monitoring

Since this project is part of my home, I shall continue to monitor it, and keep it in good working repair. The DNRC is welcome to visit at any time.

V. Public Availability

We estimate approximately 500 people have been through our home since it has been built. The public is welcome to visit at any time provided we are notified by telephone in advance so a mutually convenient time can be arranged. Most of our visitors are from the western Montana area, although some people from other states as well as Canada have been through. The response has always been very positive.

VI. Program Evaluation

I sincerely feel this program is worthwhile. The demonstration of alternative energy in actual functioning units that people can see is very important. Four short years ago when I started looking into alternative energy systems the general word from officialdom was, "it is 30 years in the future." They cannot say that anymore, because almost everyone has talked with a person who is making it work now. As we accelerate into the Solar Age, programssuch as this will have played no small part.

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I. Solar Collector Box Construction

Of major consideration in building flat plate collectors is the box which will house the collector surface. Many different factors must be considered and weighed and a decision made on the basis of this analysis. The criteria for consideration undoubtedly vary from installation to installation; however, some general criteria should apply in most cases. Among these are:

A. DURABILITY--many solar collectors are placed in fairly inaccessible locations (roofs, etc.) and it is desirable to keep maintenance to a minimum.

B. COST--to be weighed against other considerations.

C. EASE OF CONSTRUCTION

D. REPAIRABILITY--ease of making repairs and/or alterations should the need arise.

E. WEIGHT--many collectors are extremely heavy, particularly glass glazed units and weight becomes a major consideration.

F. ENVIRONMENTAL CONSIDERATIONS--such as wood and cardboard are renewable resources; glass is plentiful and energy efficient to produce; fiberglass is a petroleum derivative, etc.

I have done considerable work and experimentation with box materials and insulation. This has proved to be a very challenging and at the same time frustrating area because the solution to one problem invariably leads to other problems. Briefly here is what I've found.

First a word about insulations, since any consideration of box design must necessarily deal with the type of insulation used. There are many types of foam suitable for flat plate collectors as well as the standard fiberglass building insulation. Some I have investigated are:

Name	Type	Cost $/ft.^2$	Thickness	R-factor / inch	Cost / R	Available
Fiberglass	Glass	11.2¢	3½"	3.14	1.0¢	Locally
Beadboard	Polystyrene	14.9¢	1"	4.17	3.6¢	Locally
Styrofoam	Polystyrene	26.0¢	1"	5.50	4.7¢	Spokane
Urethane Board	Polyurethane	25.0¢	1"	7.30	3.4¢	Seattle or Salt Lake
Foil Board	Foil Lined Polyurethane	39.0¢	1"	8.33	4.7¢	Salt Lake or Minneapolis

Polyurethane with foil faces is the best insulation per inch of thickness, but also the most expensive per R factor received. It would appear fiberglass building insulation is most cost effective, however the extra depth required to obtain comparable R factors must be taken into account. This sometimes makes it more expensive, depending on the material used. Both polystyrene products melt at collector temperatures sometimes experienced and in my opinion should not be used for this reason.

The following cost figures are for a 34" X 76" size collector.

WOOD BOX -- This is the method used for my original 100 ft.^{2} of collector which has been in operation for one year.

Advantages -- Locally available, easily workable, renewable resource, can be built to accomodate any insulation.

Disadvantages -- Extremely heavy, moisture in wood sometimes condenses inside collector, fairly frequent maintenance required with just painting, warping can cause leaks.

Cost -- Can be the cheapest of all methods, depending on type and grade of materials used. Cheaper materials would tend to require more maintenance. Good materials would be:

½" AC plywood (for back)	$10.00 (considerable waste)
#1 2" X 6" X 18' (for sides)	6.00
Waterproof adhesive	3.00
Nails	.50
Paint--two coats inside and out	5.00
3½" fiberglass insulation (R-11)	2.50
TOTAL--insulated to R-12 back and R-5 sides	$28.00

ALL FIBERGLASS BOX

Advantages -- Excellent weather durability, no maintenance problems, high strength, very light, (25# with insulation), no moisture problems, easy repairability.

Disadvantages -- High cost, petroleum product.

Cost

20# resin @ 51¢	$10.20
9# matt @ 70¢	6.30
20 ft.^{2} veil @ 2.3¢	.46
½ gal. Gel coat	5.00
Releasing wax	1.00
38.5 BF urethane foam @ 25¢	9.63
TOTAL--insulated to R-8 sides and R-16 back	$32.59

FIBERGLASS WITH CARDBOARD CORE

In an attempt to lower the material cost of the all fiberglass unit a cardboard core was constructed using laminated ribs of beadboard and cardboard as stiffeners. The box was deepened to accomodate fiberglass insulation in back. Three of these units were built and fiberglassed.

Advantages -- Material greatly reduced (approximately one half), good strength, very light weight (20#), as well as the previously mentioned advantages of fiberglass.

Disadvantages -- Slightly more labor, sharp corners on cardboard were hard to fiberglass, beadboard melted on test unit.

Note: One of these units was double glazed after being painted entirely flat black inside and used to test various materials at a high temperature. Materials tested in the unit included:

Beadboard (plain) -- Melted
Beadboard (foil wrapped) -- Melted
Beadboard (fiberglassed -- Melted
Fiberglass insulation -- No deterioration
Fiberglass coated on cardboard -- No deterioration
Two paints -- No deterioration
Polyurethane foam (plain) -- No deterioration
Polyurethane foam (under fiberglass) -- No deterioration

Temperatures recorded for two days reached 245° F. and 265° F.

Cost

Cardboard core	$ 2.00
Beadboard in edges and stiffiners	3.42
10# resin @ 51¢	5.10
5# matt	3.50
20 Ft.^{2} veil @ 2.3¢	.46
½ gal. gel coat	5.00
White glue	.50
Fiberglass insulation for back	2.02
TOTAL--insulated R-5 sides and R-12 back	$22.00

In applications where temperatures above 200° F. would never be encountered this would be an ideal box--light, strong, and long lasting. Such installations may be antifreeze-filled convective flow systems where high temperatures should never be encountered. If there is a chance of occassional higher temperatures however, polyurethane must be substituted for the beadboard in the laminating process. The idea then occured to me to fiberglass directly onto the polyurethane and eliminate the cardboard altogether, since polyester resins are completely compatible with polyurethane foam. Test panels proved quite promising.

POLYURETHANE CORE FIBERGLASS BOX

Advantages -- As well as the advantages already listed for fiberglass, the insulation is an integral part of the box protected on all sides. R-factors are high. The box can be made thinner and lighter.

Disadvantages -- not available locally, high freight costs, petroleum products throughout.

Cost

38.5 BF of polyurethane board @ 25¢	$9.63
White glue	.50
15# resin @ 51¢	7.65
7# matt @ 70¢	4.90
20 ft.^{2} veil @ 2.3¢	.46
½ gal. Gel coat	5.00
TOTAL--insulated R-8 sides and R-16 back	$28.14

26 GAUGE GALVANIZED METAL BOX

Since most people do not have the facilities to fabricate out of metal, I requested a price from a local sheet metal shop completely made up.

Advantages -- should be relatively maintenance free and last well, fairly light weight.

Disadvantages -- Boxes would be excellent conductors of heat and therefore must be insulated extremely well, fairly unattractive if left unpainted.

Cost

Cost per unit of 20 or more	$27.85
38.5 BF polyurethane board @ 25¢	9.63
Glue	2.00
Total Cost (unpainted)	$39.48

SUMMARY

Type	Cost	Approximate R-Factors
Good Quality Wood	$28.00	R-5 sides; R-12 back
All fiberglass	32.59	R-8 sides; R-16 back
Cardboard Core	22.00	R-5 sides; R-12 back
Polyurethane Core	28.14	R-8 sides; R-16 back
Galvanized Metal	39.48*	R-8 sides; R- 16 back

*Includes most fabricating

II. Reduction of Collector Plate Material

An examination of materials to use for flat plate collectors usually ends with copper, aluminum, and steel. Investigation shows, in general terms, that copper has an ability to move heat twice that of aluminum and eight times that of steel. It also has the lowest corrosive properties of the three used with water, and is therefore the obvious choice for flat plate collectors.

The high price of copper, however, very often eliminates it from consideration. Cost/benefit/durability relationships are extremely difficult to analyze. Hence every solar enthusiast has his or her own favorite materials combinations and good reasons why! If prices were equal however, there is little doubt copper would prevail.

One method to reduce the cost of all copper collectors is to reduce the amount of copper used in them to the point that

A. the copper used is carrying all or nearly all the heat energy incident to it;

B. there is no "extra heat-carrying capacity" in the form of excess copper;

C. methods can be found to adequately handle copper this thin.

How thick must the copper be? A very interesting and intriguing question! Theoretical calculations show very thin copper indeed will handle solar incidence. Using the formula: $H = k\,A\,\frac{T_1 - T_2}{L}$

Where: H = heat of conduction (BTU/HR)

A = area (ft.^{2})

T_1 = degrees F. (high temp.)

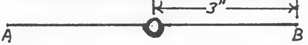
T_2 = degrees F. (lower temp.)

L = thickness (distance from tube in iches)

K = coefficient of thermal conductivity (BTU $\cdot$ In/Hr $\cdot$ Ft.^{2} $\cdot$ F$^{\circ}$)

for copper = 2.7×10^3

Assume:
1. Tube spacing of 6 inches (that used on my current heavy gauge collector).
2. A maximum available 350 BTU/Hr.
3. It all hits at points A and B, half each place or 175 BTU/Hr.



4. Plate size of 2 ft. long by 6 in. wide giving 1 ft.^{2} collecting area.
5. A water temperature in collecting tube near maximum of 150° F. and excess heat at point A or B of 300° F. ($\Delta T = 150°$).

Solving for A which in this case will give us plate thickness:

$$A = \frac{LH}{k(T_1 - T_2)}$$

$$A = \frac{(3)\ (175)}{(2.7 \times 10^3)(300 - 150)}$$

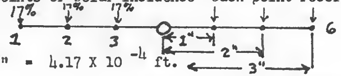
$$A = \frac{525}{4.05 \times 10^5}$$

$$A = 1.296 \times 10^{-3}$$

$$A = .0013$$

This indicates a copper plate thickness slightly in excess of one thousandth would carry 350 BTU/Hr with 6 inch tube spacing. The thinnest copper foil I could find is called 4 oz. (4 ft.^{2} = 1#) and measures .005". It should therefore theoretically carry enough heat. Using the same formula and solving for H:

Assume:
1. 6 inch tube spacing
2. BTU/HR = 350
3. 6 points of solar incidence--each point receiving 17% of total



Converting: $.005" = 4.17 \times 10^{-4}$ ft.

Then: $H_{\text{point 1 or 6}} = (2.7 \times 10^3)(4.17 \times 10^{-4})\left(\frac{300-150}{3}\right)$

$H_{\text{point 1 or 6}} = 56.3$ BTU/HR

If 17% hits each point then points 1 or 6 each have 59.5 BTU/Hr. incidence. Therefore, this thickness should carry it. To test the ability of 4 oz. copper to function as well as heavier gauges, it was first necessary to solve the fabrication problem. Commonly milled thicknesses of copper are:

16 oz. ---- 1 ft.^{2} = 1# ---- .022"
12 oz. ---- 1 1/3ft.^{2} = 1# ---- .017"
8 oz. ---- 2 ft.^{2} = 1# ---- .011"
4 oz. ---- 4 ft.^{2} = 1# ---- .005"

My previous solar collectors had been 6" spaced $\frac{1}{2}$" copper tubing soldered to 16 oz. (.022") copper. I experienced considerable difficulty during the soldering operation with the copper plate buckling. My idea was to groove the copper 5/8 inch to accept the riser tube. This should:

1. increase the strength by providing two right angles near the tube soldering point, and
2. Form a good fit so the solder would flow by capillary action thereby assuring a good "sweat" connection and decreasing the amount of solder used.

A machine was built using male and female parts to accomplish this. It will roll six grooves at 6" spacing simultaneously by turning the hand crank. It rolls copper and aluminum easily and will roll steel up to .015" thickness. I found this to make a tremendous difference in soldering and no problems were experienced fabricating any of our test panels; even the 4 oz. copper soldered without buckling.

A friend and fellow grant recipient, Mr. John MacDonald, and I cooperated on the test runs on tube spacing and plate material and thickness. The considerable cost and time consuming data taking were shared by us.

Two test collectors were built using the cardboard and laminated polystyrene method described herein, except they were not fiberglassed or painted.

Collector fact area was 3 ft.^{2} in each box. The boxes were designed so that the 3/16" crystal glazings could be removed for replacement of different collector faces. Each box was connected to identical five gallon insulated tanks by rubber heater hose and clamps and ran by convection. We ran the following comparisons.

A. Tube spacing of 4", 6", and 8" on 4 oz. copper back.

B. Tube spacing of 6" on 16 oz. copper back.

C. .015 galvanized steel back with steel conduit tubes using 6" spacing.

All collector faces were of the header-riser tube design.

Two general types of tests were run:

1. Same amount of water in each unit, same initial temperature, units allowed to run all day and final temperature checked.
2. Same as above except half hour readings were taken (after stirring contents) for graphing purposes.

It was decided to use the 16 oz. heavy copper with 6" spacing of riser tubes as a control, since my operating collectors have performed well and at efficiencies comparing favorably with those reported by the industry. This control unit was run on each trial, and will hereafter be referred to as "control". The actual measurement of the control unit was 2.86 ft.^{2}. Since each unit varied slightly in size, the area for each is given in the heading of the test results which follow.

TEST--6"SPACING ON 4 OZ. COPPER (2.76 ft.^{2})

	DATE	WATER WEIGHT	ΔT^oF	TIME	BTU/HR/FT^2
CONTROL	July 19	40#	71.1	6.5	153
TEST		40#	66.6	6.5	149
CONTROL	July 21	40#	53.1	5.5	135
TEST		40#	52.2	5.5	138
CONTROL	July 22	40#	17.1	6.0	N.A.--129.2° water was T_1 & ran all day to test high temp. comparison
TEST		40#	15.3	6.0	
CONTROL	July 28	41#	77.4	6.5	171
TEST		40.5#	71.1	6.5	161
CONTROL	August 3	40#	51.7	3.0	248
TEST		40#	51.4	3.0	241

TEST--6" SPACING ON .015 GALVANIZED STEEL (2.87 ft.^{2})

CONTROL	July 29	40#	82.0	8.0	143
TEST		40#	74.0	8.0	129

TEST--4" SPACING ON 4 OZ. COPPER (2.77 ft.^{2})

CONTROL	August 1	40#	34.5	3.5	138
TEST		40#	32.0	3.5	132
CONTROL	August 4 a.m.	40#	59.4	4.25	196
TEST		40#	59.4	4.25	202

TEST--8" SPACING ON 4 OZ. COPPER (2.84 ft.^{2})

CONTROL	August 3	40#	64.8	3.86	235
TEST		40#	55.8	3.86	204
CONTROL	August 4 p.m.	40#	28.8	3.5	115 (cloudy)
TEST		40#	26.1	3.5	105

CONCLUSIONS

1. Within the limits of experimental error the 4 oz. copper with 6 inch tube spacing seems equal to or very nearly equal to the 16 oz. copper control. Average figures for BTU/HR/FT^2 show the control at 176.75 and the 4 oz. at 172.25. The difference of 4.5 BTU/HR/FT^2 is not significant. This is very encouraging since it brings the price of copper collector plate from \$3.61/ft.^{2} (for 16 oz.) down to \$.90/ft.^{2} and reduces the weight by 75%!
2. Considerable dropoff in BTU/HR/FT^2 is shown by galvanized steel even at .015 thickness and considering the rust and corrosion problems and the price of 4 oz. copper, it is probably not a competitive choice.
3. Not much is gained by 4 inch tube spacing. If you move all the heat that is there with 6 inch spacing this is understandable.
4. Eight inch spacing shows significant drop off in efficiency.

III. Plate Coating

It has recently been widely reported among solar energy enthusiasts that some shade of green is superior to black at absorbing sun energy and would therefore be beneficial to use as the color of flat plate collectors. When questioned few can recall exactly where they read or heard this.

A search of the literature by the National Solar Heating and Cooling Information Center turned up just one article, apparently the origin of all the reports. A copy of their reply to my inquiry is enclosed. I also wrote directly to the University of Florida and have enclosed a copy of their reply.

To run some preliminary tests of my own on various shades of green I obtained the four primary tints used in coloring green paints. These tints are manufactured by Tennaco and are called:

A. "LF Medium Green"

B. "LF Light Green"

C. "Thalo Green"

D. "Chromium Oxide"

My general procedure was to mix increasing amounts of each tint with basic white enamel until the darkest possible shade was obtained with each tint. In addition a yellow tint was added to one test can in each group in order to match as nearly as possible the reported "elm leaf green" color. American elm upper leaf surface was used as a color guide. I have attempted to match each resulting color as closely as possible with color patches obtained at the Columbia Paint Store and have included them herein.

Group A: "LF Medium Green"

1. 322M ASPARAGUS
3. 324A SOUTHERN PINE

2. 323D GARLAND
*4. 347A GLORY GREEN

Group B: "LF Light Green"

5. 352 M SERENDIPITY
6. 354 A HOLLY WREATH
7. 359 A WINTERGREEN
*8. 360 JUNGLE VINE

Group C: "Thalo Green"

9. 221 M BUTTONWOOD
10. 222 D MONTEGO BAY
11. 282 D GARDEN GROTTO
*12. 281 M GREENELLA

Group D: "Chromium Oxide"

13. 375M GREEN GULL
14. 376M TENDRIL
15. 377D BRANWOOD
*16. 378 D CANADA GREEN

Group E: Ready Mixed Paints

17. Duponts Porch & Floor Enamel--Dark Green
18. Duponts Wrought Iron Flat Black

*Some yellow added

Each of the eighteen shades of paint was coated on an aluminum can on all surfaces except the bottom where the color mixture was coded. These were then filled with exactly ½# of water each (in case BTU calculations would later be desirable). The initial trials were run by simply sitting all the cans in the direct sunlight in a protected location. The purpose of these initial runs was to choose the more promising shades for further testing. Several trials were run but the data of the best solar day is included below. (See slide #1)

Group A: "LF Medium Green

	12:00	1:00	2:00	3:00	4:00
1.	57.2	75.2	77.0	79.2	80.2
2.	57.2	76.1	78.4	82.4	82.4
3.	57.2	77.0	78.8	82.8	82.4
4.	57.2	77.0	78.8	81.0	82.4
Group B: "LF Light Green"					
5.	57.2	75.2	77.0	79.2	80.2
6.	57.2	75.2	77.9	80.6	81.7
7.	57.2	76.1	77.9	80.2	81.0
8.	57.2	75.2	77.0	79.7	80.6
Group C: "Thalo Green"					
9.	57.2	76.6	78.8	81.0	81.0
10.	57.2	77.0	79.2	82.0	82.4
11.	57.2	77.9	80.4	82.8	82.8
12.	57.2	77.9	80.2	82.4	82.4

	12:00	1:00	2:00	3:00	4:00
		Group D: "Chromium Oxide"			
13.	57.2	76.1	77.7	80.6	80.6
14.	57.2	77.0	78.8	81.9	81.5
15.	57.2	76.6	78.8	81.5	81.0
16.	57.2	77.0	79.2	82.0	81.0
		Group E: Ready Mixed Paints			
17.	57.2	80.6	82.4	82.6	80.6
18.	57.2	83.3	86.0	82.6	82.4

The best performer of each group is graphed for July 2. Preliminary indications were that black was superior but certain variables such as wind cooling at uneven rates had to be eliminated.

In order to make the simulation as nearly like actual conditions as possible a long box with six identical cubicles was constructed from polystyrene foam. Each cubicle had 2" polystyrene top, back, and bottoms, with 1" polystyrene divisions between cubicles. The face was tightly sealed with 3/16" crystal glass (single pane). Each cubicle fit an aluminum can with approximately $\frac{1}{4}$" on all sides. (See slide #2.)

The top six performers were each filled with $\frac{1}{2}$# of water and sealed in this apparatus. Small holes covered with tape allowed a thermometer to be inserted from the top without opening the glass cover. Again several trials were run with the data for July 7th included below.

July 7th was an excellent solar day. It had rained the day before so the atmosphere was clear. The sky was cloudless, there was no wind, and the air temperature was 82^{o}.

The graph for July 7th follows.

Data Sheet for July 7, 1977

	10:00	11:00	12:00	1:00	2:00	3:00	4:00	5:00
A-3	59.5	75.4	98.4	116.6	134.6	147.2	149.0	145.4
B-6	59.7	74.8	97.7	113.5	132.3	145.4	149.2	145.4
C-11	60.8	77.4	98.6	119.7	138.2	152.1	154.0	149.0
D-16	59.9	76.5	93.2	111.6	129.4	143.6	147.4	144.3
E-17	60.1	78.6	96.8	116.8	134.4	149.0	152.1	147.2
E-18	59.4	79.0	100.4	122.2	140.0	152.1	154.0	145.4

Temperatures are given in Farenheit

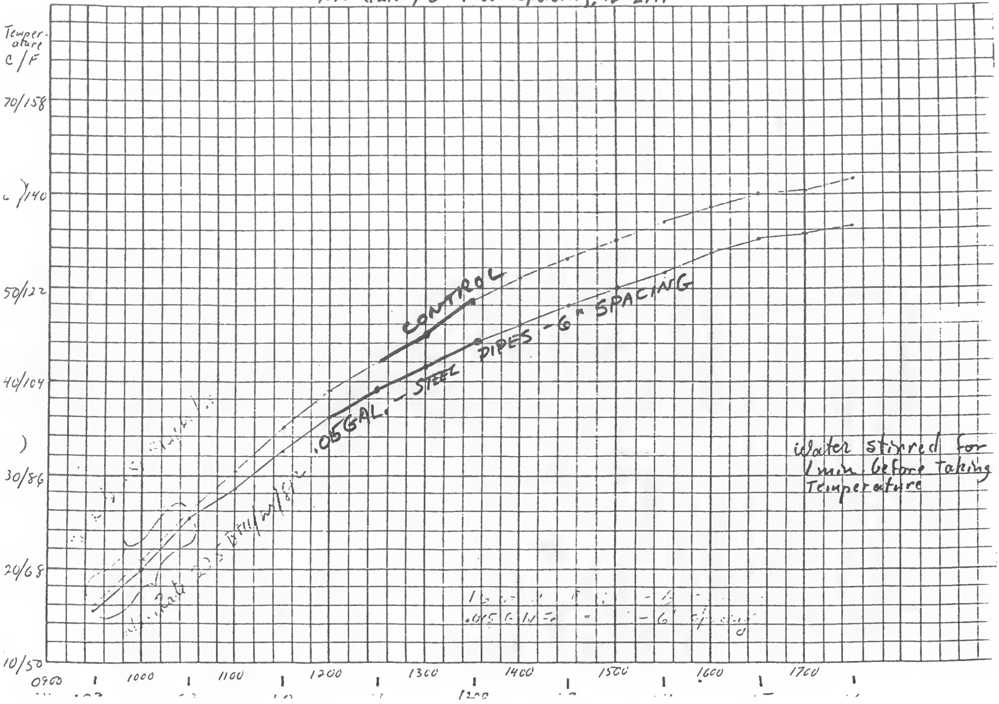
General Conclusions

1. Black absorbs more energy per unit of time than any green color tested, although the difference between black and the better shades of green is surprisingly small.
2. Roughening the surface of the cans with relatively frequent and deep scratches with course sandpaper seemed to have no detectable effect.
3. A sprinkling of very finely chopped aluminum foil bits sprinkled into the still wet paint and then covered with additional paint was tried. This dried into an extremely rough surface. This procedure decreased efficiency.
4. Columbia flat black implement paint is slightly superior to Dupont wrought iron black, probably because it has less "sheen". Ace fast-drying enamel in flat black looks even more dull, although not actually tested against the other two.
5. All three withstood heat tests of 275° well without peeling or cracking.

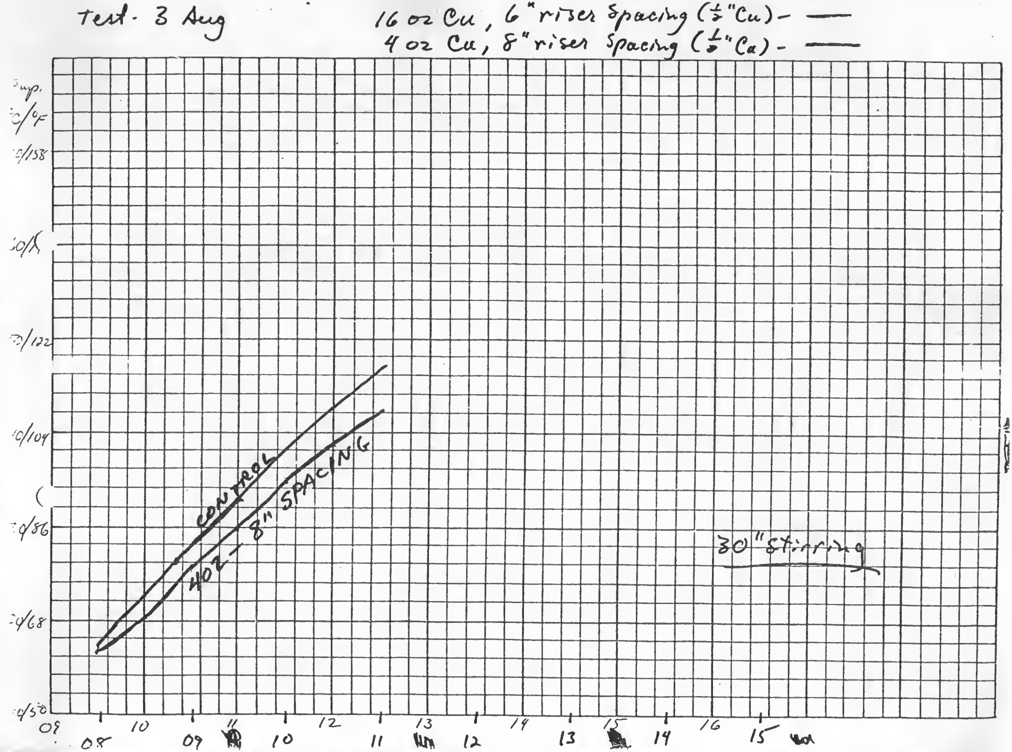
Test. 29 July

16 oz. Cu, 6" riser spacing, ½" Cu
.015" Galv., 6" riser spacing, ½" EMT

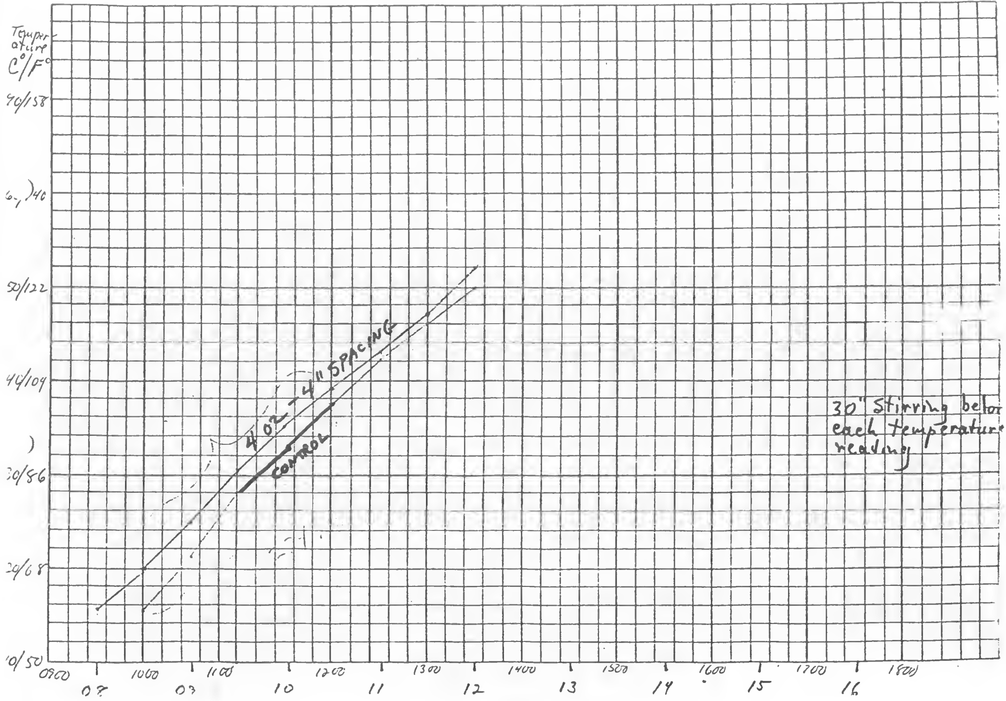
5.0 gal. H_2O each



Test - 3 Aug

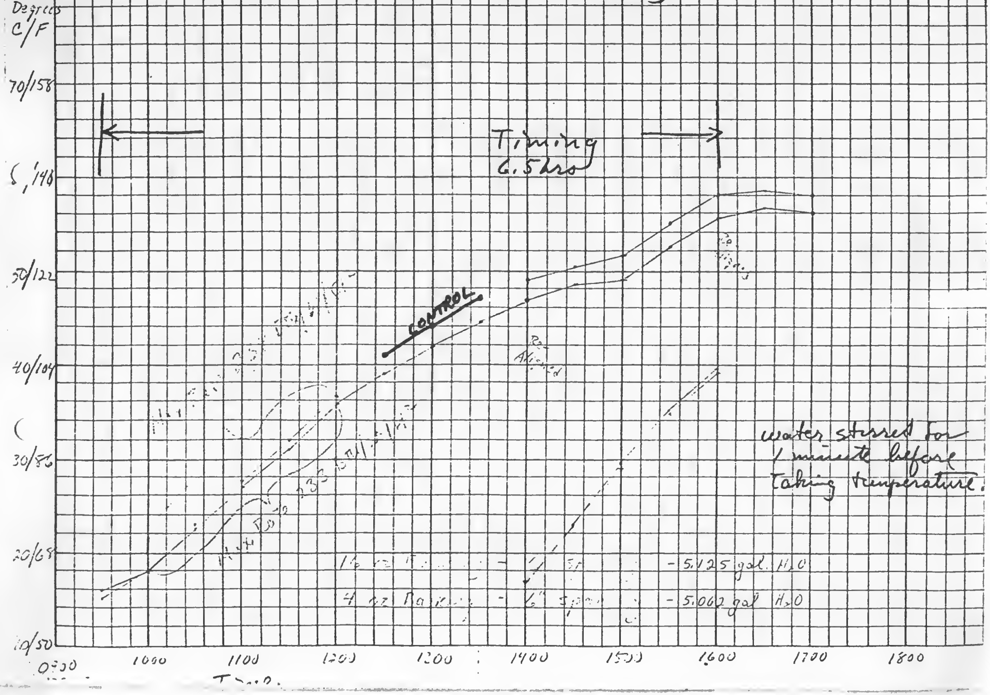

16 oz Cu, 6" riser spacing (½" Cu) -
4 oz Cu, 8" riser spacing (½" Cu) -
Temp.
°C/°F
/158
/1
/122
/104
/86
/68
/50
09
08
10
09
11
10
12
11
13
12
14
13
15
14
16
15
CONTROL
4OZ - 8" SPACING
30" stirring

Test - 1Aug 16 oz, Cu, 6" riser spacing (½" Cu) —— 5.0 gal H_2O
4 oz, Cu, 4" " " " —— 5.0 gal H_2O



Tests- 28 July
Intermittent clouds

16 oz Cu, 6" riser spacing
4 oz Cu, 6" riser spacing



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A COMPARISON OF AIR COLLECTOR DESIGNS

I. Theoretical Considerations in Air Collector Design

A survey of the literature on solar heating and collector design finds most advocates firmly entrenched in one of two camps--the air vs. water collectors. While most authorities and commercial companies seem to have decided in favor of water collection as being the most efficient, many air advocates continue to insist that the advantages of air collection outweigh efficiency considerations.

There are several advantages of air systems which I will examine separately:

A. Lower Cost--In some air collector designs it is possible to lower the costs considerably by eliminating costly tubing and materials (such as copper) in the collector surface. Indeed, several designs call for recycled type of materials, such as aluminum cans. These types of materials are generally easily and reasonably available.

B. On-Site Construction--Some designs feature on-site construction out of standard available construction materials, with ho special training required by construction personnel. The advantages here are obvious. A good example of this type of collector is the "screen" collector designed by the University of Maine and tested by the Maine Audubon Society. Standard aluminum window screen is stapled to plywood in this design, which is one of the ones I tested.

C. More Useable Energy--The reasoning here of the air collector advocates is that most of us heat our homes with forced hot air. It makes sense then to supply heated air directly, rather than to exchange the heat from heated water or other mediums.

D. No Chance of Freezing in Cold Climates--The danger of water collectors freezing in cold weather makes this an obvious advantage of air systems.

E. More Architectural Leeway--It is possible with some air systems to design the system as an integral part of the structure being constructed. Thus a vertical south wall can sometimes be the collector surface. This would then free the architect from traditional sun angle and roof angle considerations, etc.

The water system advocates will point out just as many advantages to their systems. It is not the intent of this project to examine these arguments in detail. Rather the above air collectors' claimed advantages are mentioned because they figure in the design and operation of air systems. The intent of this project is to compare several types of air collector designs from several standpoints such as cost, efficiency, ease of construction, etc.

There are several things found in the literature which affect the efficiency and design of air collectors. These can be grouped into general design and theoretical considerations. The major ones are outlined below.

A. Collector Face Material--the material of which the collector face is constructed is going, to some degree, to determine how efficiently the collected heat is transferred to the circulating air. Generally the collector face is of some type of metal, usually aluminum or steel, rarely copper. Of the three copper is the best heat conductor, followed by aluminum and then steel. If steel is assigned a value of 1, then in general terms, aluminum would be 4X and copper 8X. In other words, copper is roughly eight times as efficient at moving heat as is steel. Obviously cost considerations will also be important.

B. Amount of Surface Area--the general theory here suggests that the more surface area of material you can cram into each square foot of collector, the more heat will be collected. There are some practical limits to this, of course, but in general high surface area is to be strived for.

C. Turbulence Of Air Flow--The collector designs should induce as much turbulence into the passing air as possible. This is to ensure air molecule contact with as much surface as possible during its trip through the collector. It also helps eliminate laminar air flow, such as air following the glass from bottom to top of collector and thereby missing much of the surface area of the hot collector surface below.

D. Even Air Distribution--Air must be distributed evenly throughout the collector surface in order to take advantage of the total square feet of the collector face. For example, if the air inlet is a hole in the middle of the bottom of the collector and the outlet is also in the middle of the top of the collector, air molecules may "take the easiest route" through the collector and travel directly from bottom to top through the center of the collector only. The sides of the collector would therefore be much less efficient and to some degree wasted. Several things can be done to solve this problem including better placement of inlets and outlets, routing the air through the different areas of the collector with baffles, creating high turbulence, etc.

In order to test the above theoretical hypothesis I decided to build actual operating collectors, but of a scaled down version. Two collector boxes were constructed approximately two feet square. The resulting four square feet of collector surface is large enough to show true operating functions and to make accurate projections, but small enough to keep cost and construction time within reason. Because each solar day is slightly different as far as incoming radiation is concerned, I decided to use two collectors in each test. The comparative figures could then be analyzed.

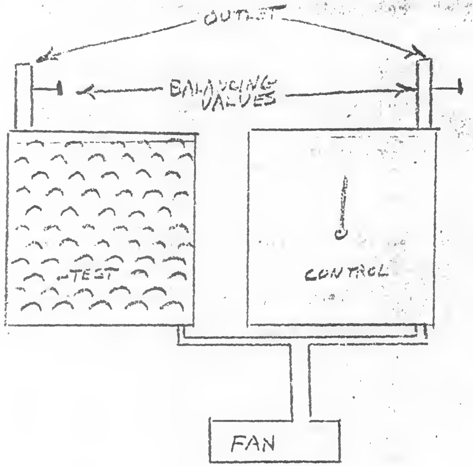
The boxes were constructed using polystyrene rigid insulation 1" thick laminated between cardboard. This gave 1 inch of foam insulation in the back and sides. An additional $3\frac{1}{2}$" of fiberglass was added inside each box, giving the back (where most heat loss occurs) a total of $4\frac{1}{2}$" of insulation. The boxes were glued together using standard white glue. To make sure no air leaked through the seams, the entire inside was given a coat of fiberglass. After the test plates were inserted, a single piece of 3/16" crystal plate glass was used to cover the front. This was secured to the boxes with duct tape and nylon strap.

Each box had an inlet and an outlet opening. These were constructed by placing 7/8" ID heater hose in holes and silicone sealing them in place. This type of hose was used because 3/4" copper pipe will exactly fit into it and can be easily clamped into place. A 3/4" shutoff valve was placed in the outlet of each box to equalize air flow. The two inlets were tied together with a common manifold using 3/4" copper pipe. One fan could then be used to supply both boxes.

The lab setup was then to construct a stand on which both boxes rested. This stand could be adjusted as to the angle to the incoming solar radiation. Both boxes were supplied with air by reversing an electrolux vacume cleaner. The blown air would enter the lower right corner of each box and exit at the upper left corner. A small wind gauge was constructed using a level and roller skate wheel bearings. With this device it was possible to balance the flow coming out of each collector by using the valves to restrict flow on the higher one. The friction, and hence the amount of exiting air, varied with each run due to different collector design. It was therefore necessary to balance the flow prior to each run. The reason for this balancing is that if the source of air is the same for each, and the amount of air moving through the collector is kept the same for each, then the only variable is the design of the collector itself, and a direct comparison can be made between the two collectors ina given run.

The general procedure for each run was then as follows:

1. Place collectors to be tested in boxes.
2. Seal glass.
3. Place on stand and adjust for proper angle.
4. Turn on fan and adjust air flow, blancing each collector.
5. Turn off fan and allow ½ hour warmup time.
6. Turn on fan and allow to run for five minutes.
7. Take temperature readings of exiting air.
8. Allow fan to run for from 15 minutes to one hour taking temperature intermittently.



It has been noted in my past work with fiberglass that it is a good absorber of radiant sunlight energy. I therefore decided to use one box without anything in it as my control. This box was painted with the same flat black paint as were the collector faces. The only item inside was a thermometer to record internal control temperatures.

I chose six different types of collector faces to test. Some of these are used widely and described in the literature. Others I tried simply because I thought they might perform well based on the theoretical considerations discussed earlier. The actual lab runs were done in two distinct phases:

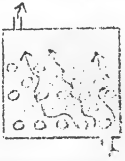
Phase 1 -- each experimental design was run against the control.

Phase 2 -- the better designs were run against each other directly under varying sunlight conditions.

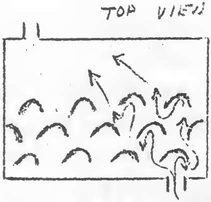
II. Description Of Collectors Tested

Six pieces of 3/4" particle board were cut to a size which would just fit into the boxes. Upon these the various collector faces were constructed. The entire 2' X 2' particle board was covered with the particular collector material, giving 4 square feet for each test collector.

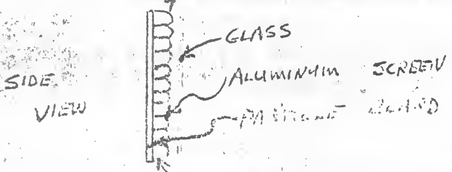
1. Half Can Collector -- There is a commercial collector on the market using this design, as well as numerous home built units. It is constructed by cutting aluminum pop or beer cans in half and usually stapling each half to plywood in a staggered pattern. To try to increase its efficiency even more I pop-riveted each half to a sheet of aluminum. This design is said to provide high turbulence as the air is forced around each can, as well as trapping radiation in each can as a small "black box".



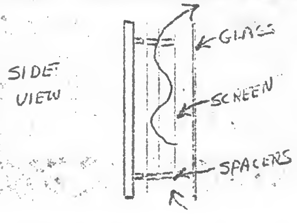
2. Fourth Can Collector -- In this design aluminum cans are first cut in half and then split again into quarters. The quarters are then stapled in a staggered pattern to the particle board. This design seemed to provide very high turbulence by making air molecules "retrace their path" and collide with oncoming molecules.

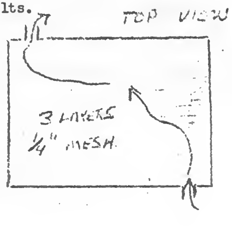


3. Screen Collector -- Developed by the University of Maine and tested in the Maine Audobon Society Visitor Center, this collector offers the most surface area of any design. Aluminum screen is stapled in loops to the particleboard. Recommended frequency is seven loops per foot.

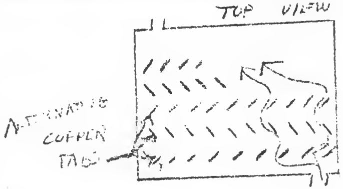


4. Steel Plaster Lathe -- Air collectors using steel plaster lathe are often described in the literature. The type I used was $\frac{1}{4}$" mesh of #10 gauge wire. Three layers of this were used with steel spacers in between. A very high surface area results.

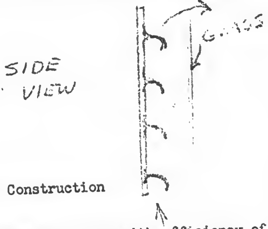




5. Copper -- I have never heard of a copper air collector, but because the material is such a good conductor of heat, I wanted to try one. "Angle irons" of copper were bent and stapled to the particle board. The up leg of each angle was cut at approximately one inch intervals and bent into a vane. The vanes were turned in different directions in succeeding rows.



6. Fiberglass Wave -- As already noted, fiberglass is a good absorber of solar energy. I decided to try to induce turbulence by making half circle waves at six inch intervals on the particle board back.



III. Ease Of Construction

The ease of construction must be considered, along with efficiency of design, when deciding upon the type of air collectors to build. Of the various types constructed, some were quite easy and others extremely difficult and frustrating. Listed below are some of the construction evaluations.

1. Half Can Collector -- A special spring loaded jig was required to cut the cans safely using a carbide blade on a radial arm saw. This rig worked nicely unless there are pop tops or cigarette butts inside, then, beware of flying material! Pop riviting to aluminum is extremely time consuming and frustrating--stapling would be much easier but one would have to find a special stapler which would reach to the can's bottom. Painting was very difficult and wasteful.
2. Quarter Can Collector -- A satisfactory jig to cut $\frac{1}{2}$ cans into $\frac{1}{4}$ cans was never found. This is a very dangerous operation as the saw throws pieces of aluminum around. A jig completely enclosing the $\frac{1}{2}$ can inside and out may be the only answer. Once $\frac{1}{4}$ can sections are at hand, stapling, painting, and the remainder of the assembly is easy.
3. Screen Collector -- This collector is fairly easy and fast to build--lining out intervals takes the most time. The procedure is to calculate the loop distance and mark it on the screen. Then calculate the interval distance and mark it on the backing. Then match the marks and staple. A piece of pipe helps keep the loops round.
4. Steel Plaster Lathe Collector -- Very easy to construct. There was some difficulty in putting in the spacers.
5. Copper Collector -- Very easy with no problems encountered. Bending the tabs does take time.
6. Fiberglass Wave Collector -- Standard fiberglassing skills are necessary. The process goes fairly fast. Two inch PVC pipe was cut in half, coated with vaseline and used as a mold for the waves. The pipe can be removed as the fiberglass cures. Holes are then drilled in each wave. Extensive cleaning is needed prior to painting to remove the vaseline.

Considering all aspects of ease of construction, I would rank these six methods as follows.

Very Easy — Average — Very Difficult

Screen   Steel   Copper   Fiberglass Wave   ¼ Can   ½ Can

The amount and cost of materials should also be considered. This is difficult to do since some materials are very expensive and others nearly free but require considerable time (cans). Also, the cans are not "free" environmentally or energy-wise. The following rankings are therefore very general.

High Cost — Average Cost — Low Cost

Copper   Screen   Steel   Fiberglass   Both Cans

High Material Use — Average Material Use — Low Material Use

Screen   ½ & ¼ Cans   Steel   Copper   Fiberglass Wave

IV. Lab Run Results

Excellent solar day. Some scattered clouds moved in about 1:00 but later dissipated.

Time	Internal Control Temp.	Control Exit Temp.	Copper Exit Temp.	½ Can Exit Temp.	Screen Exit Temp.	Fiberglass Exit Temp.	Steel Exit Temp.	Notes
10:30	56.1°C	45°C	39°C					
11:20	58.3°C	46°C		49°C				
12:25	68.3°C	50°C			50°C			
1:15	65.6°C	47°C				41°C		①
2:20	67.2°C	49½°C				49½°C		②
2:35	56.6°C	46½°C				50°C		③
3:30	60.0°C	45½°C					44°C	
3:45	47.8°C	40°C					39½°C	③

① Clouds moving in, ew unit (fiberglass) possibly not fully heated up.
② Sun out again brightly.
③ After 15 mins. consecutive running.

High Scattered clouds--hazy but some sun coming through.

Time	Internal Control Temp.	Control Exit Temp.	¼Can Exit Temp.	Copper Exit Temp.	Notes
12:15	60.0°C	44°C	49½°C		
1:10	56.1°C	41°C		38½°C	
1:25	59.6°C	42.8°C		39½°C	3

3 After 15 minutes consecutive running.

Hazy overcast day with sun showing through. Comparison of ½ and ¼ can collectors.

Time	½ Can Exit Temp.	¼ Can Exit Temp.
12:05	41°C	39°C
12:10	36°C	38°C
12:15	37°C	38°C
12:20	36.5°C	37°C

Good Solar morning--cloudy in the afternoon. Comparison between ¼ can and fiberglass.

Time	¼ Can Exit Temp.	Fiberglass Wave Temp.	Notes
9:37	--------	----------------	Both units put out
10:24	--------	----------------	Motor turned on
10:27	50°C	49.5°C	In both units the temperature was climbing despite the fan being on.
10:30	51°C	50°C	
10:38	52°C	50°C	
10:49	54°C	52°C	
10:50	--------	----------------	Motor turned off

Continued next page.

Time	¼ Can Exit Temp.	Fiberglass Wave Temp.	Notes
11:18	--------	--------------	Motor turned on
11:22	65°C	64°C	Collectors nearly vertical to simulate
11:31	60½°C	58½°C	wall installation.
11:34	--------	--------------	Motor turned off
2:09	37°C	39°C	Motor turned on for
2:37	40½°C	43°C	almost half an hour.

Based upon Phase I & II runs I would rank the tested collectors generally as follows:

Best			Control		Worst
¼ Can	Fiberglass Wave	½ Can	Screen	Steel	Copper

The ¼ and ½ can and the fiberglass wave collectors were by far the better. The bare control box was as good as the screen collector and slightly better than the steel collector. The copper collector was far from the others in performance.

V. General Conclusions

1. Turbulence is more important than either surface area or type of material. The high turbulent collectors (both cans and fiberglass wave) did well. The high surface area collectors (screen, steel) did only average and the best conducting material (copper) did the worst.
2. The collector glass seems to be an important collecting surface. Those high turbulent collectors which threw molecules against it did well. Also the collector face close to the glass was better than a space between the glass and the face. The two can collectors actually touched the glass.

3. The ultimate in air collector design would seem to combine high surface area with turbulence-causing devices. For example, baffles could be put within each loop of the screen collector giving both turbulence and area. I'm not sure the extra materials and time would warrant this, however.
4. Fiberglass seems to outperform the metals during overcast, marginal solar conditions.
5. Based upon a consideration of all factors I have decided to build 180^2 ft. of fiberglass wave collectors to heat my shop.

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